2.—BEACH SAND MOVEMENTS AT COTTESLOE, WESTERN AUSTRALIA.

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CONTENTS.

ABSTRACT.

Investigation into the serious erosion of the beach at Cottesloe lead to more widespread investigation into the general movement of sand in the area known as Cockburn Sound and Approaches to Fremantle. The movement of sand throughout the area and the mechanics of the sand movements at Cottesloe are discussed in relation to the various conditions of weather, currents and wave actions.

I. INTRODUCTION.

Cottesloe is situated at 31° 59′ S., by 115° 45′ E., on the west coast of Australia, about 3 miles north of Fremantle Harbour and approximately 8 miles from Perth. From the year 1900 to about 1940 Cottesloe was a fashionable bathing beach and summer resort, but owing to increasing beach erosion that has become especially apparent since 1940, the popularity of the beach has declined, so that by 1950 the bathing pavilion and other amenities built in 1929 were no longer showing a profit.

In 1906 a jetty had been built after the style of the piers of the south of England, having band stands, etc., along its length. The beach then was quite extensive. The next major " improvement " was in 1929, when a large bathing pavilion with shops and other amenities was erected. A retaining wall and promenade were built along the front of the buildings, thereby encroaching slightly on the beach. Also, a large parking area was built on the dunes just north of the pavilion. At this time (1929) there was still ample sand to form a good beach.

About 10 years after the pavilion was built it became apparent that the sand was getting thinner, as during heavy winds and storms the rock below the beach was being uncovered. This condition has steadily deteriorated until now the beach is often unusable because of jagged underlying rock being stripped bare of sand for the greater part of the summer. The jetty is still in existence, but, owing to damage by storms and lack of maintenance, is less than one quarter its original length.

In 1949 the Cottesloe Council, through its Councillor Mr. F. G. Forman, former Government Geologist, and Dr. R. W. Fairbridge, of the University of Western Australia, agreed to help defray the expense of beach erosion investigation, which led to the writer undertaking one year's research on this problem as part of his fourth year of study in geology at the University of Western Australia under the direction of Dr. Fairbridge. The Council met the cost of the air photos taken by Airsurveys Pty., Ltd., during the year, and also defrayed the incidental expenses arising during the investigation.

The method of work was, firstly, an extensive reading of the literature available, together with frequent visits to the beach. From preliminary observations and the information gained from the literature, it was apparent that some type of standard observation sheet would be necessary. Thus an outline table of observations to be made on each visit was drawn up and used throughout the investigation. The original table was amended later in the year to give a more complete coverage of the variable factors.

From the outset it was realised that a continuous record of the weather conditions would be necessary, so the daily weather bulletins were obtained from the Divisional Meteorologist, Perth, and these were invaluable, especially when used in conjunction with the air photos.

During the year, six vertical line-overlap aerial photograph runs were flown ; run 1 taking in the beach from 3 miles south of Cottesloe to a point approximately 10 miles north of Cottesloe ; runs 2–6 being only repeat coverage of selected portions of run 1. Some selected obliques were taken at specific times, but there was no attempt to give any sort of general coverage by obliques. These photographs are kept in the Geology Department of the University of Western Australia.

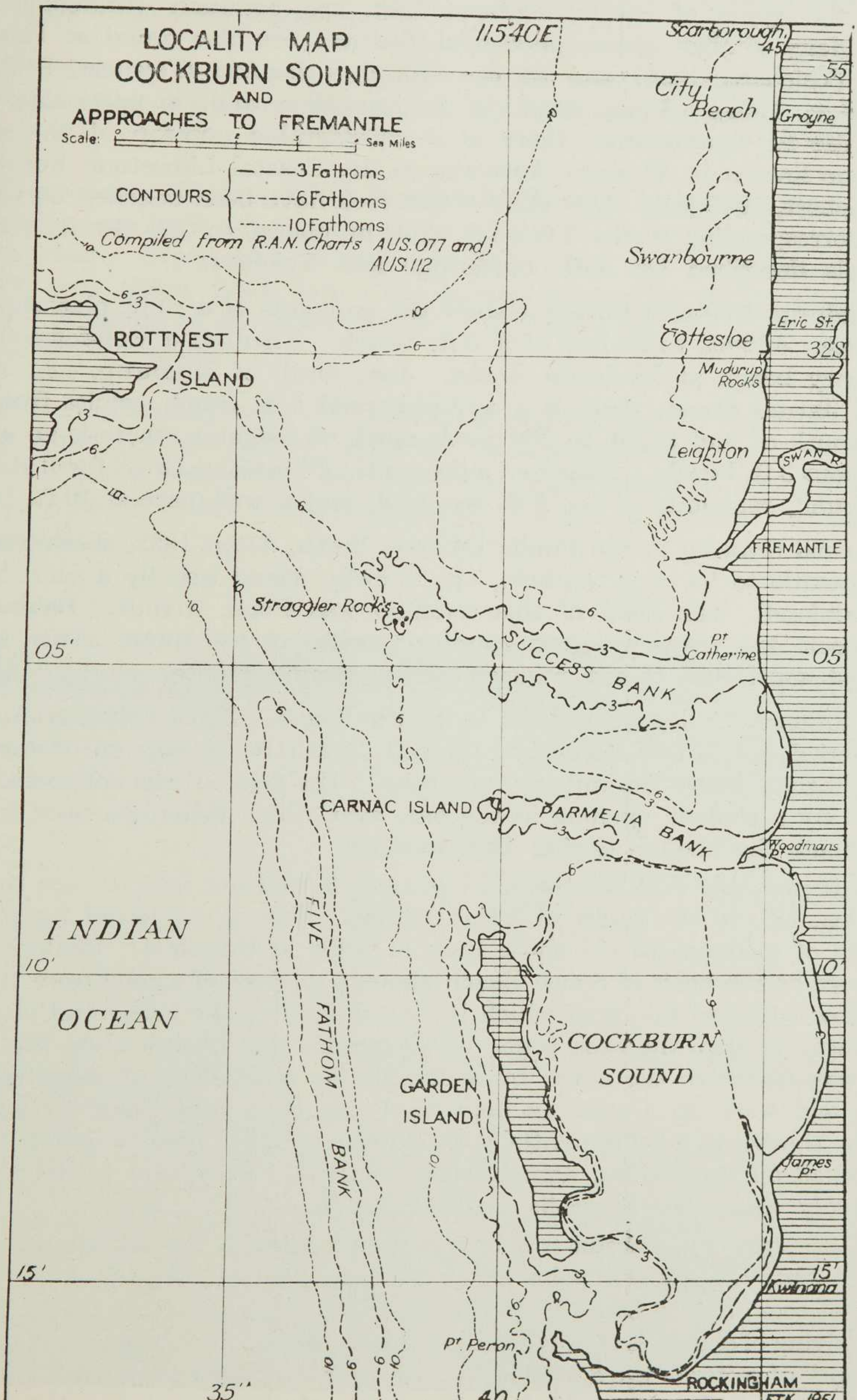
Details of the above aerial photographs, together with the tides for the preceding 48 hours and the winds for the previous four days, are given in Appendix I.

Some attempt was made to study the problem of beach erosion using sedimentary petrographic methods, following the methods and conclusions of Krumbein (1941) and Rittenhouse (1943a, b), but owing to many factors beyond control and the fact that all the sand originated from the same distributive province, namely the Pre-Cambrian of the West Australian Shield, it was realised that little result could be expected, and consequently the time was devoted to other avenues of approach.

Finally, the writer would like to express his wholehearted thanks to the Cottesloe Council for making this investigation possible, to Dr. R. W. Fairbridge, whose guidance and advice has been of very great assistance, and to Mr. N. J. Henry of the Harbours and Rivers Branch of the Department of Public Works, for his co-operation and information.

II. GENERAL DESCRIPTION OF THE AREA.

Before dealing with Cottesloe in particular, general consideration is needed of the unit area, which may be taken as Cockburn Sound and the approaches to Fremantle (*see* Locality Map, text fig. 1).



Text fig. 1.

General locality map showing Cockburn Sound and the approaches to Fremantle.

A comparison of the old maps of Archdeacon and Coghlan, prepared in 1874 with the 1947 R.A.N. charts, shows that, in general, only minor variations have occurred in the distribution of offshore sediments. The two sand banks in Cockburn Sound, namely Parmelia and Success Banks, have not changed to any noticeable extent.

Coastal Features.—In a paper on Point Peron, Fairbridge (1950) described the types of coastal features that are common throughout the area. Many similar geomorphological features are also found at Rottnest Island (Teichert, 1950) and at the Abrolhos Islands (Teichert, 1947 (b), Fairbridge, 1948). Along much of the coastline and, in particular, from Fremantle to Swanbourne, there is a considerable outcrop of the sandy limestone known in Western Australia as the Coastal Limestone Formation (*see* Teichert, 1947 (a)). Low cliffs of this rock have been benched at various levels corresponding to the 3 ft., 5 ft. and, in places, to the 10 ft. eustatic sea-levels described by both Fairbridge and Teichert.

Mudurup Rocks at Cottesloe show the remnants of a 10 ft. platform and, to a lesser extent, evidences of a 5 ft. bench. There is a well-formed contemporary bench at Mudurup Rocks. Just south of Mudurup, *i.e.*, at the foot of Jarrad Street, there is a well-preserved 5 ft. bench, whilst from 100 yards south of that bench to 200 yards north of Leighton, there is an almost continuous 3 ft. bench. Some two miles south of Cottesloe two " fossil stacks " were found, remnants of the 5 ft. sea-level, and a well-marked 10 ft. bench.

An old drawing in the Public Library, Perth, dated 1832, shows the site of Fremantle to be on a tombolo, *i.e.*, a rocky island tied by a sand bar to the mainland. The head of this tombolo was Point Arthur. Behind the South-east Beach was a lagoon running parallel to the shore. This lagoon was just south-east of the position of the Round House.

Another such lagoon existed at South Beach. Until reclamation work was carried out by the Fremantle Council, South Beach was an offshore bar with a lagoon where the railway now runs. This lagoon was connected with the sea by a shallow opening in the bar, over which fishermen used to take their boats for shelter during bad weather.

It is probable that the Swan River once flowed out into the sea through this area, *i.e.*, to the south of Point Arthur. This is suggested by the discoveries of evidence of old shore lines in wells in this area. Shallow holes put down at the back of South Beach about a quarter of a mile from the sea, also show bands of fine mud which is very much like the river mud of today. This suggests that the area south of Fremantle was once a river flat. The river was forced to the north by a cumulative movement of sand from the south, and took up a position between Point Rous and Point Arthur.

To the south of Fremantle is Cockburn Sound. This sound is almost landlocked on three sides, namely east, south and west, and to the north is practically sealed by Parmelia and Success Banks.

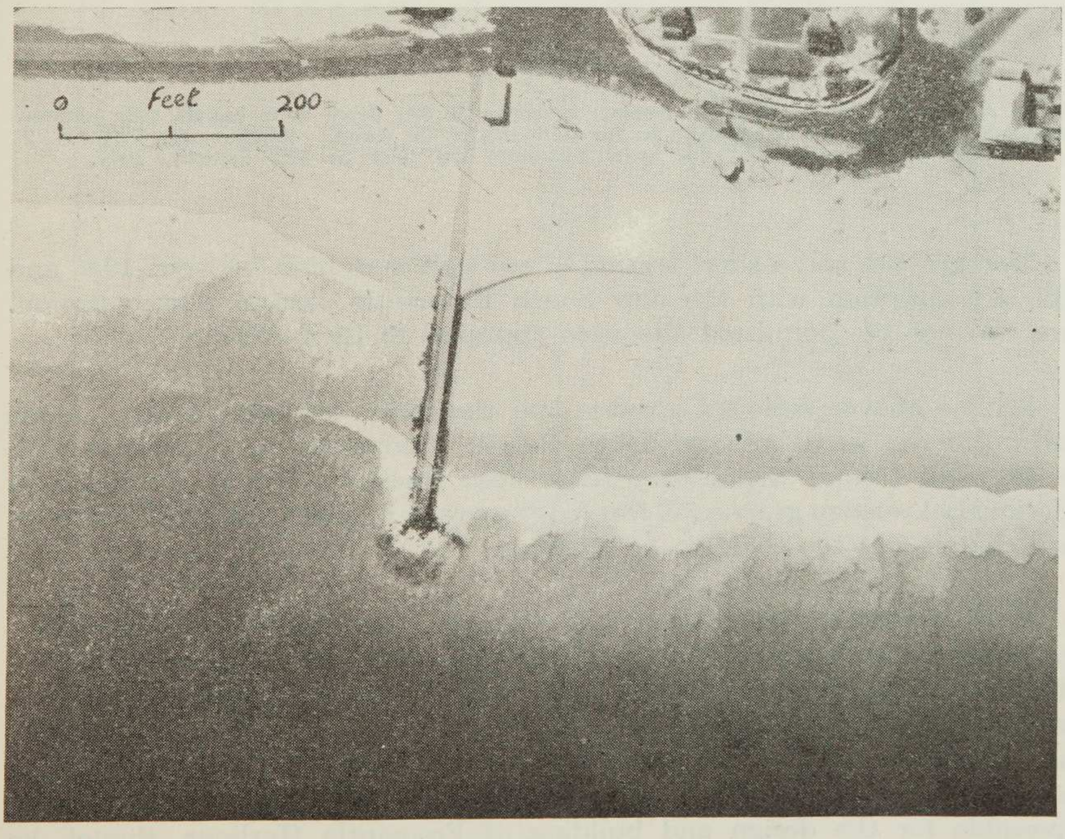
These two banks trend roughly at right angles to the coastline (*see* text fig. 1). They are not controlled by a rock bar structure, *i.e.*, they do not have a core of rock, but as far as is known are composed entirely of sand. During the dredging of channels through these banks nothing but sand was encountered. The depth of water in the Sound is down to 10 fathoms (60 feet), while the banks rise abruptly to less than 10 feet of water and are almost awash in places. The bottom of Cockburn Sound is a grey calcareous ooze.

Analyses of sand from the banks show about 95 per cent. carbonate (from N. J. Henry, Public Works Department, personal communication), suggesting either that it is of littoral drift origin, *i.e.*, composed of light current-born material, or that the banks are the site of former shell colonies that are now extinct. These sands are extremely fine so that the second hypothesis is unlikely. Because of their high carbonate content, it is most probable that the banks are composed of sand derived from broken shells and transported by littoral drift from beaches farther along the coast. Grant and Shepard (1940) found that similar banks built up in deep water in Santa Monica Bay, California, were composed of fine sand of high carbonate content, and mostly finer than 0.125 mm. diameter.

Woodman's Point and Catherine Point were probably both formed by building up of sand on the eastern end of the banks by wave and wind action.

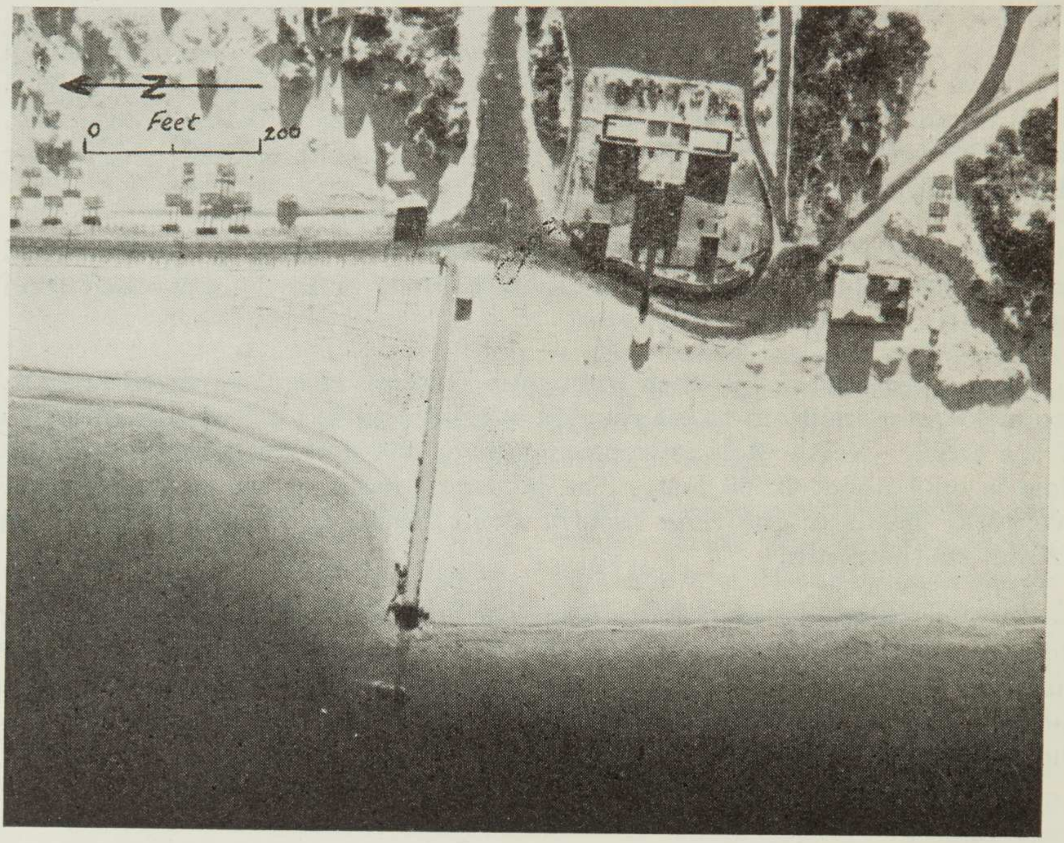
Engineering Works.—When Fremantle Harbour was constructed in 1890, two moles were built out to sea roughly at right angles to the general direction of the coast. North Mole is approximately 5,000 feet long, whereas South Mole is only about 2,500 feet. The landward bases of the moles were the two rocky heads of the river mouth, Point Rous on the north and Point Arthur on the south.

A short masonry mole or groyne was built about 15 years ago at City Beach, some 6 miles north of Cottesloe. This groyne is 400 feet long and was built for beach protection, and from the result observed was a complete success, a broad beach always forming on one side or the other according to the season.



Text fig. 2.

Winter conditions at the City Beach groyne are shown in this vertical of the beach. (North is to the left of the groyne looking from the sea.) A comparison with Text Fig. 3 shows the marked difference between summer and winter conditions.



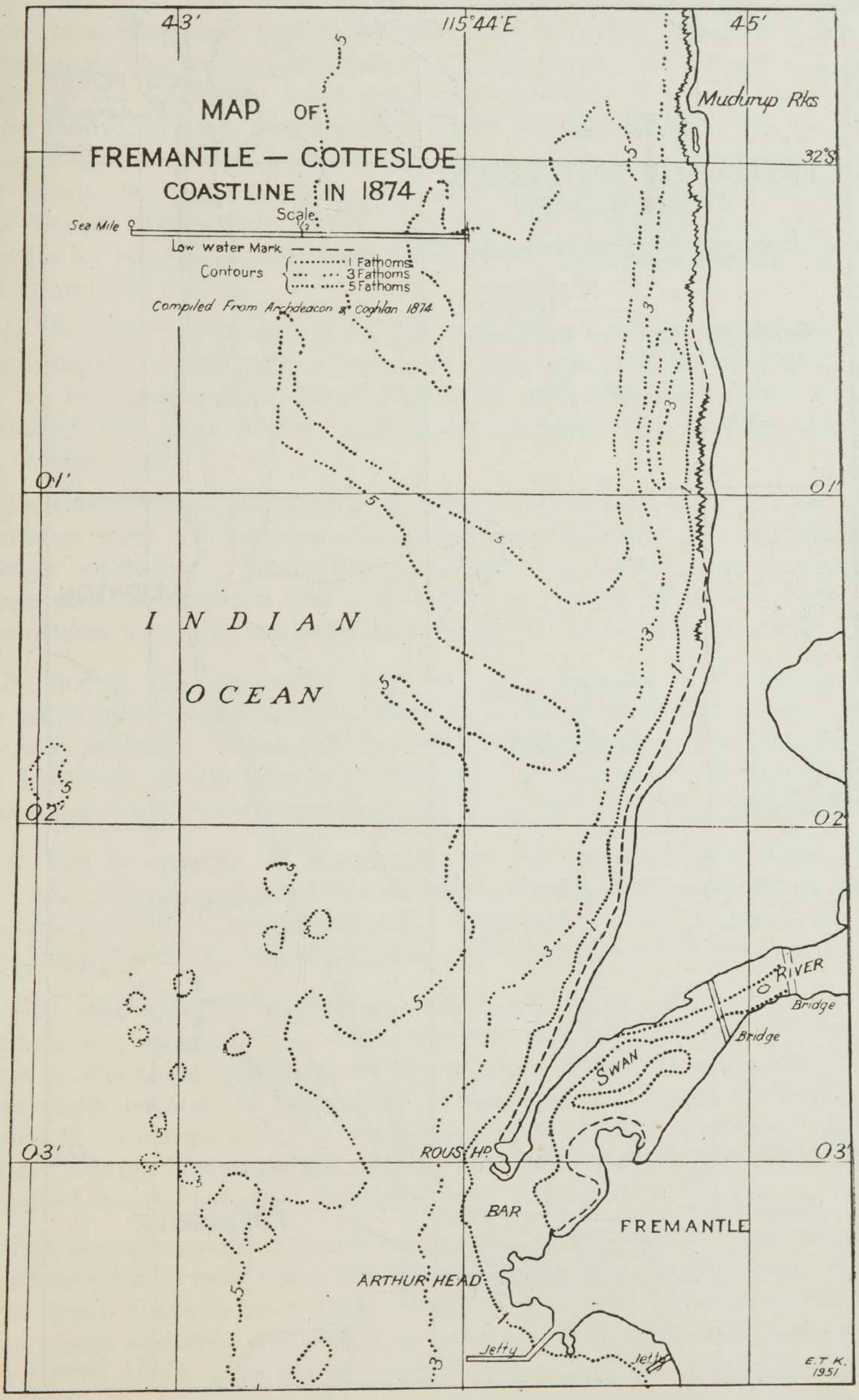
Text fig. 3.

Portion of a vertical aerial photograph showing the groyne at City Beach as it appears under summer conditions of maximum sand accumulation on the south side of the groyne. (Compare with Text Fig. 2 showing winter conditions). The aerial photograph was taken on 14th February, 1949.

Two groynes and a short section of sea wall were built between 1946 and 1949 in connection with the new South Fremantle electric power station. Time has not yet permitted adequate appraisal of their effect.

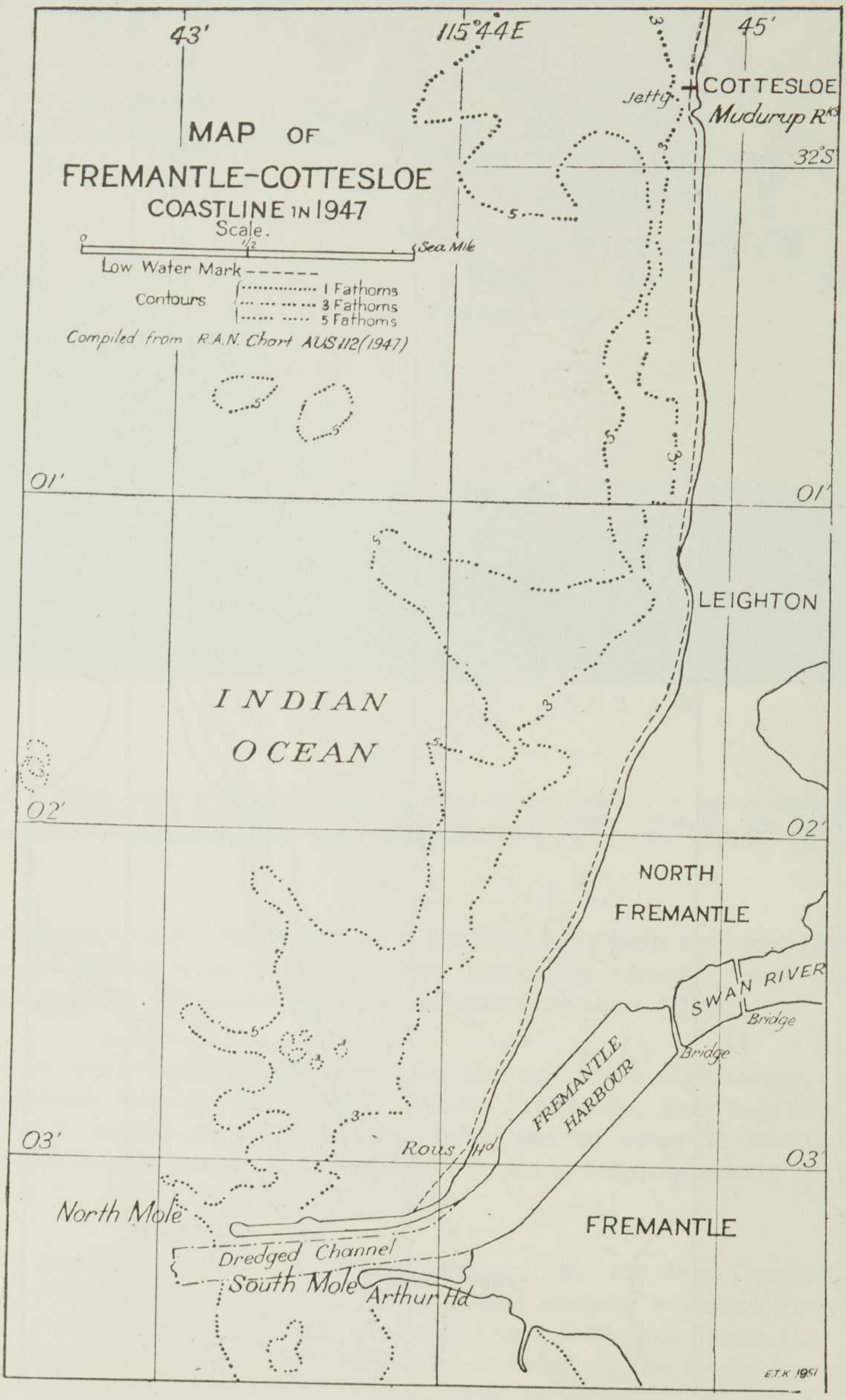
All the abovementioned groynes and the wall were of masonry. Some timber groynes were built at South Beach, Fremantle, but, together with the sea wall behind them, they have been washed away in storms. An experimental wooden groyne (56 feet long) was put in near the base of Cottesloe Jetty, but it was too short to be effective.

Sand Movement.—More than half a century ago, Sir John Coode, in his capacity as consultant engineer for the proposed harbour works at Fremantle to be built for the colony of Western Australia, came to the conclusion that there was considerable sand movement across the mouth of the Swan River and that the essential movement was from north to south. This opinion was supported to a large extent by C. Y. O'Connor, who was the principal engineer responsible for the design and building of Fremantle Harbour, though he considered that the movement of sand was not as great as Coode had suggested. It has long been recognised that there is a movement of sand along the coast in both directions at certain seasons and in certain weather conditions (to be discussed below) but it is the *net* transport of sand that is significant.



Text fig. 4.

The coast from Fremantle to Cottesloe as it was surveyed in 1874. Compare with Text fig. 5, which shows the coast as it was surveyed in 1947. Note the conditions existing in the mouth of the Swan River prior to the building of Fremantle harbour.



Text fig. 5.

Map of the Fremantle-Cottesloe area, as it was surveyed in 1947. Compare with Text fig. 4 showing the same area as it was surveyed in 1874.

Since the building of the moles and other engineering works, it has become apparent that the main movement of sand is the reverse of the direction suggested by Coode and O'Connor, *i.e.*, south to north. If the movement of sand had been north to south, then Cockburn Sound would have silted up rather than have two banks formed across the northern end of the Sound. Rather, it is suggested that the banks were formed from sand derived from beaches along the west coast south of Garden Island. This sand, having been worked to the north by wind and wave action around Garden Island and Carnac Island, is then distributed towards the east, across the north end of Cockburn Sound in two parallel sand banks. The exact nature of this movement is not clear, but from the evidence of the formation of the tombolo to Point Peron (Fairbridge, 1950), it seems fairly certain that the principal migration of sand along the west coast of this State is from the south rather than from the north.

If the sand movement is in this direction, as suggested above, there is a sand supply continually coming into the area. This sand has not only built up the area around South Fremantle and Fremantle itself, as already mentioned, but prior to the building of the moles also supplied sand to the area to the north.

To the north of Fremantle the sand movement is along the beach in accordance with the seasonal variations, and subjected to the normal action of beach conditions. There is no evidence that there were major areas of accumulated sand before the time when the North Mole was built. As in the southern area the net sand movement is in a northerly direction.

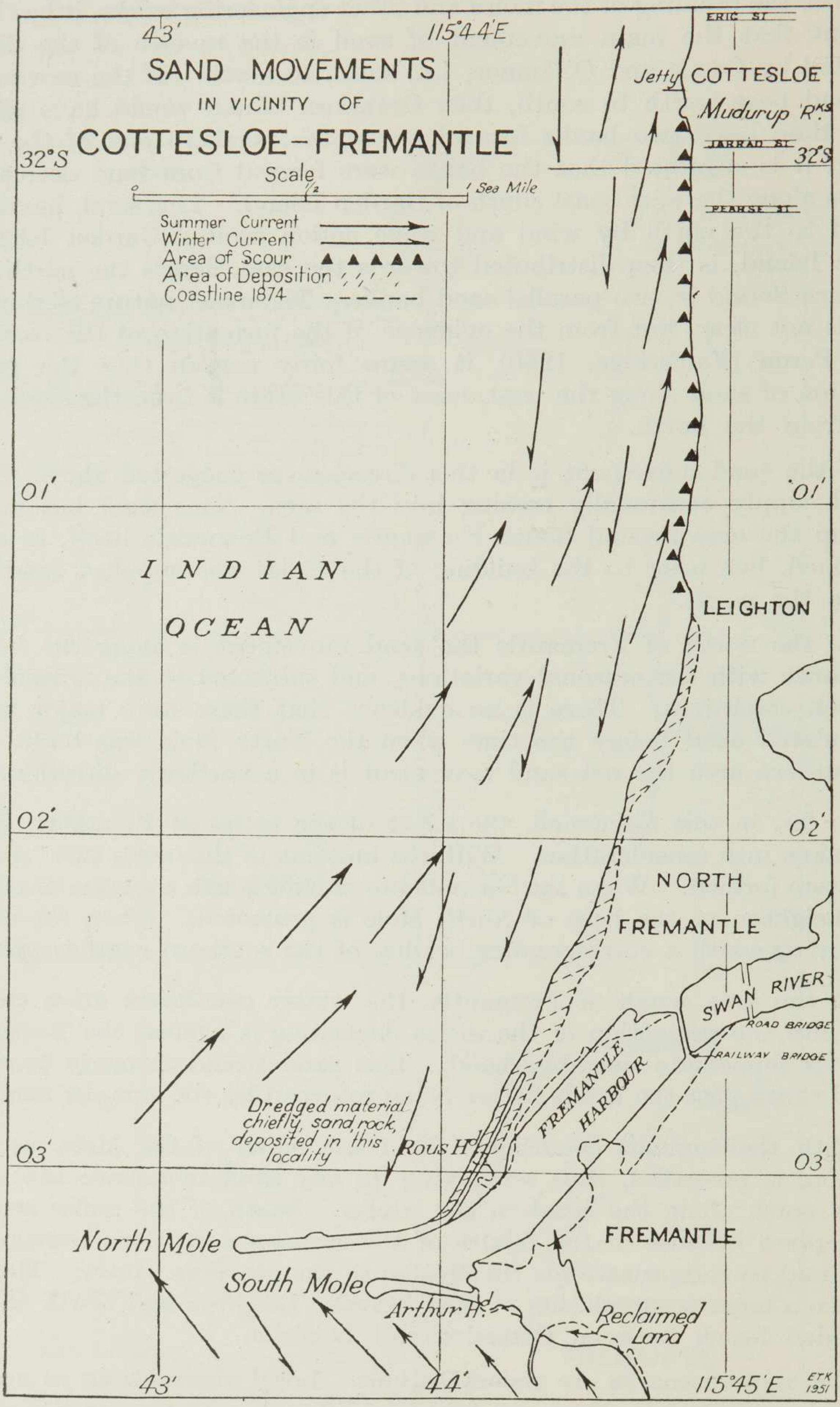
So far, in this discussion, the effect of the moles at Fremantle has not been taken into consideration. With the building of the moles two "shadow" areas were formed. When the currents are moving north a section of the coast from Leighton to the base of North Mole is protected. When the currents are moving south a corresponding section of the southern coast is protected.

In the area north of Fremantle, the winter conditions drive the sand south into the protection of the moles depositing it against the North Mole, or in its immediate neighbourhood. This sand would formerly have been carried south past the heads before being returned by the summer conditions.

With the summer conditions, the coast north of the Mole, as far as Leighton, is protected, thus not giving up any sand to replace that eroded farther north along the coast in the winter. South of the moles erosion is taking place because of the failure of the summer conditions (causing sand deposition) to compensate for the erosion of the previous winter. The result has been a large accumulation of sand between Leighton and North Mole and an eroded beach between Cottesloe and Leighton.

The above remarks are generalisations. Local observations at appropriate points seem to bear them out fairly consistently. In the south (Cockburn Sound area), there is very little silting in progress. The Parmelia Bank is almost stable and does not show any tendency to deposit sand along the shore, either to the north or to the south of the bank. A spit has built out parallel to Parmelia Bank at right angles to the trend of the shore ; a wooden groyne put in near this spit does not show any accumulative deposits on either side (*i.e.*, according to the Chart AUS. 077).

At South Fremantle Power Station there is a strong southerly drift during the N.W. winds. As the S.W. winds have only a limited fetch they do not produce a strong drift to the north, with a result that erosion takes place at Pt. Catherine.



Text fig. 6.

The Fremantle-Cottesloe area showing the dispositions of the summer and winter currents, the areas of accumulation and erosion of sand since the area was mapped in 1874. Most of the changes around Fremantle are reclamation for Harbour works and town sites, but north of the North Mole the changes are due to wave and wind action.

North of the mole there is an accumulation of sand between North Mole and Leighton Beach, an erosional scouring of sand between Leighton and Cottesloe, and from Cottesloe to the north there is a more or less even balance between summer and winter conditions.

Other beaches along the coast to the north show varying characteristics. Swanbourne Beach has not changed materially in 15 years since the Surf Life Saving Club was built, according to the Club's president.

At City Beach, from information supplied by Mr. J. Edwards of the City Engineer's Department, the net variation in the high water mark in several consecutive years formerly showed a loss by erosion of 14 feet annually. The erosion was also about the same rate at the storm water outlet from Herdsman Lake. This outlet is some three-quarters of a mile north of City Beach. When the City Beach groyne was built about 1935, however, the erosion stopped not only at City Beach but also at the storm water drain.

The effect of a groyne here was satisfactory, as predicted by the engineer, who had observed that in this area there are two distinct sets of currents, one a northerly current during the summer which was much stronger than the southerly current which was active during the winter. The relative strength of the currents can be inferred from the fact that the sand on the south side of the groyne will build up to a maximum in a shorter time than it will build up on the north side. In fact, the maximum accumulation of sand on the north side requires at least 4 days of continual strong north-west winds.

The precise reason why it takes 4 days to reach maximum accumulation on the north side of the groyne is not perfectly clear. Many factors come into such considerations. For instance, if the sea was very rough and the waves were breaking beyond the end of the groyne, as may happen in very rough weather, then the normal action of the sand movement by waves would tend to by-pass the groyne. If the wind were to shift a few points north of west, it is quite likely that a rip may be set up on the north side of the groyne, thus carrying sand out to sea and defeating the purposes of the groyne.

Observations of the effect of the groyne during a strong S.W. gale show that the area of scours beyond the groyne is situated approximately 300 to 400 yards to the north. It is felt by the City Council engineers, that if the groyne were extended then serious scouring would take place north of the groyne. The scouring at present is not very noticeable, although a few years ago erosion almost undermined the roadway in that area.

At Scarborough, from information of old residents and other observers, the beach is slowly building up. No official information is available concerning the beaches north of Scarborough, but from the reports of various people interviewed, it is not likely that any serious erosion is taking place there.

No attempt has been made to deal with the conditions in Fremantle Harbour, as it was considered that this would necessitate some specialised study. In the investigations to date the influence of the river on the beach erosion and movements of sand does not appear to be important.

III. WEATHER, CURRENTS AND TIDES.

(1) *Weather.*

Daily weather bulletins provided values for the wind strength and direction for Fremantle, Perth and Rottnest. The figures for Fremantle were used mainly, as this station is only three miles along the coast from Cottesloe, although Rottnest, being some 10 miles offshore, gives a better indication of the conditions out to sea.

During the beach observations the wind velocities were estimated, using the Beaufort Scale. It was found with experience that the estimates were reasonably accurate when compared with readings for Fremantle. The wind systems experienced along the west coast of Australia are described in the "Australia Pilot" (Vol. 5), and more recently have been co-ordinated in an "Atlas of Climatic Charts of the Oceans" (U.S. Dept. of Agriculture, 1938), where the average wind for each month has been calculated over a unit area of approximately five degrees of longitude by five degrees of latitutde. The information was compiled from ships' logs collected over many years.

From November to March, inclusive, the summer months, the dominant winds are the local land and sea breezes. The force of the land breeze rarely exceeds two on the Beaufort Scale, blowing from the east and south-east. Being an offshore breeze this has a pronounced damping effect on the ocean swell. During anticyclonic conditions, when the wind blows from the east for several days without change, the sea is usually reduced to a state not unlike the proverbial "mill pond." The sea breeze, on the other hand, is a wind often blowing with Beaufort force 3 or greater. Its direction is predominantly from the west and south-west. This breeze builds up considerable waves in the form of a short choppy sea with every wave a "white horse." On an average summer day the land breeze blows from about 3 or 4 a.m. to about midday, then there is a sudden reversal in direction and generally by 1 p.m. a strong sea breeze will be blowing. This "breeze" will blow strongly until about 6 p.m. then die out to almost still air by midnight.

April is a month of indefinite and variable wind conditions with the the possibility of an early winter storm. From May to September there is a period of winter storms alternating with near calms. These storms are up to gale force with north-west and west winds backing to gusty south-west winds. September only has occasional storms, and October is again a month of mild indefinite winds.

It is apparent then that the period of most consistent and steady winds is during the summer months rather than the winter. The effect of the summer winds is therefore dominant and particularly the more powerful "sea breezes."

(2) *Currents.*

Schott (1935) has compiled a map of the Indian and Pacific Oceans showing the distribution of ocean currents for the months of August-September and February-March. These maps show a south moving current off the west coast of Australia for the winter period, and for the summer period a north moving current with a south moving swirl next to the coast. However, these movements are ocean currents and do not necessarily correspond to the directions nearest to the coast. For instance, the sea breezes mentioned above would have very little effect on the ocean currents, as they are restricted to a belt only up to 20 miles wide.

Study of the surface drift from bottles released over the continental shelf by the C.S.I.R.O. Fisheries Branch (by courtesy of Dr. Serventy), show that generally off the Western Australian coast from Bunbury to Geraldton, there are two dominant sets. One is a relatively strong northerly set being effective from September to April of the average year, whilst the other is a southerly, but weaker set, running from June to July and sometimes into August.

During May and August-September, the drift is changeable as are the winds during these two periods. The above results are for an average year and should serve only as a general guide as to what may be expected. There is in fact a great variation in the figures from year to year and with varying seasons. In the year of study (1949) it was thought that the drift changed from south to north in November, as it was not until then that sand started to move north.

(3) *Tides.*

The tidal effect at Cottesloe is very limited in that the total variation on a daily range averages only about 18 inches. It is fortunate that the nearest tide recording station is only three miles away at Fremantle, and as conditions are very similar the figures may be taken as closely indicative of those for Cottesloe. Bennett (1939) summarised the tidal conditions at Fremantle. Fairbridge (1950) gives the following summary of tidal conditions: "Mean sea-level there was determined in 1933 at 2.27 feet above datum (fixed by harmonic analysis at lowest low springs); the annual range of mean sea-level however, was found to be 1.26† feet. The neap range is about one foot and the mean spring range about three feet . . . . However, with the annual swing of mean sea-level, we get an overall mean spring range of something over five feet."

As pointed out by Curlewis (1916), meteorological conditions also exert a profound influence on tides, high pressure systems, keeping the level low, and cylconic (low) systems keeping the level high.

The highest recorded tide at Fremantle is 6.25 feet (in 1920) and the lowest was minus 0.5 feet (in 1896). However, the physiographic effect of such abnormal tides does not appear to be important.

It is considered by the writer that as the daily variation of tide is so small, then the area can be classed at almost "tideless," *i.e.*, the effect of the tide in relation to other factors, such as waves, etc., can be neglected.

IV. OBSERVATIONS AT COTTESLOE.

The engineer, Sir Benjamin Baker, once said "Nature never deceives you, if you watch her long enough." It is hoped that the year spent observing the effect of Nature's forces on the beach at Cottesloe was long enough to give a sufficient knowledge and understanding of the inter-reaction of the wind, wave and sand, in order to give a reasonably clear picture of the problem and to suggest a satisfactory treatment.

In dealing with Cottesloe in particular, it is proposed to consider:

1. The changes observed during the course of this year's observations, *i.e.*, Diurnal and annual changes,
2. the change over the years from a good beach to a poor beach, *i.e.*, progressive changes,
3. the causes of the changes that have taken place, as indicated by the evidence available.

(1) *Diurnal and Annual Changes.*

A brief discussion of the terminology and process of beach erosion is needed as an introduction to this section.† Many authors have recognised that during periods of storm the sand beaches are flattened and the sand

* There appears to be a misprint in Bennett's paper stating that is 2·26 feet.

† *See* Johnson (1919), Shepard (1948) and Kuenen (1950) for shore-line characteristics and terminology.

moves seaward tending to form a bar at the plunge line. The sand may move out in two ways ; it may be carried out

(i) by rips,

or (ii) by the resultant backwash of the waves.

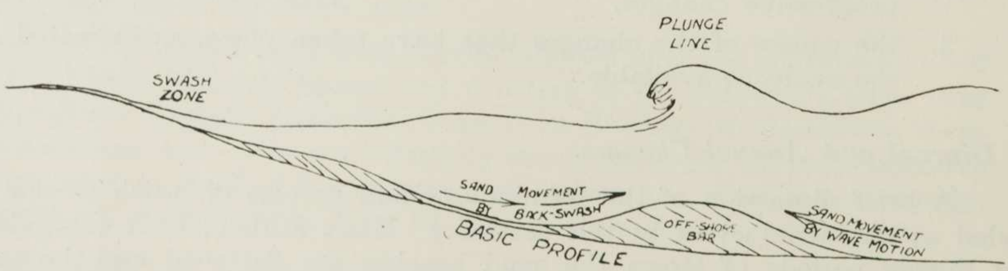
(i) Transport by Rips : Rip currents are defined as seaward moving currents of water which return the water carried landward by waves (Shepard, Emery and La Fond, 1941). It is considered by O'Brien (1950), Inman (1950), Horrer (1950) and Monk and Traylor (1947), that wave refraction concentrates the energy of the waves onto one section of the coast (dependent on bottom contours) and from the centre of that section the water returns to the sea in the form of a strong current or rip.

The workers at the Scripps Institute favour this explanation (*i.e.*, rip currents) for the bulk movement of sand out from the land during periods of strong onshore winds. Such currents attain a considerable velocity and transport appreciable quantities of sand. They are the true rip currents and often correspond to the so-called " undertow " that is commonly reported on many beaches. In general, the rips tend to form in the centre of the bays and have feeders parallel to the shore. The general direction of the current is at right angles to the beach. Sand carried in the scouring current is usually deposited again within 400 yards of the beach, *i.e.*, about twice the distance of the plunge line from the beach.

The sand of the sand-bank which is formed as a result of the rip depositing its load offshore, is subsequently returned shorewards by the normal action of the oscillatory waves after the rip current has ceased to flow.

Rips have also been noticed when there is little or no wind. One was seen at Cottesloe this year during a calm period when a heavy swell was running. This rip was very strong and persisted for more than 24 hours. The wind at the time was a very light E.S.E. breeze. On many occasions rips were seen at Cottesloe long after the wind had died down, but before the heavy swell of a storm had subsided.

(ii) Transportation by Backswash : When a wave breaks, the bulk of the water moves forward in a translatory motion. With the advent of the next wave, the swash of the last wave moves back to the plunge line bringing sand part of the way with it. If the backswash is stronger than the swash, then the sand gradually moves out towards the plunge line. Offshore from the plunge line, sand is moving landwards with the normal oscillatory motion of the waves. Thus, there are two forces moving sand towards the plunge line, each reaching maximum movement at the plunge line. This brings about the building of a sand bar (*see* particularly King and Williams (1949)), in a paper on the formation and movement of sand bars in a tideless sea).



Text fig. 7.

Diagrammatic sketch of the building of an offshore bar.

A sand bank built on the basic shore profile will only remain stationary whilst the height of the top of the bank above the basic profile is less than half the depth of the water above the bank. Thus, when a heavy sea is running, the sand from the beach is moved into a sand bar at the plunge line. But when the sea subsides and the depth of water above the bank becomes less than twice the height of the bank above the basic profile, then the bank is moved shorewards. That is, as the plunge line moves towards the shore, due to the subsidence of the swell, the offshore bar will also move with the plunge line. If the swell subsides so much that the waves are breaking close to the shore, then the bar will not form again but the sand will mount up onto the shore to form a " swash bar " or " whale back."

Grant (1943) recognises a similar occurrence at LaJolla, California, after storms. Bars are formed parallel to the shore during the storm, but after the storm these bars are moved towards the land. There is selective transportation of the sand by the waves as these bars are moved landwards (*see* also La Fond (1940)).

The conclusion may be drawn that with a strong onshore wind or in storm conditions, the actual beach is being eroded or retrograded, but in the relatively calm period after a storm or during an offshore wind, the beach progrades or builds up.

* * * * * * *

At the beginning of systematic observations at Cottesloe (first record, 27–3–1949) the beach was in a very bad state. The sea bed from the plunge line outwards was rock, and for the most part, bare of sand. In the southern portion of the bay a large area of rock was exposed along the beach. During the afternoon of 27th March, a strong sea breeze blew from the south-west with a Beaufort Scale force of 3. In an area just south of the jetty to just north of the jetty, sand was eroded rapidly and transferred north towards the northern limits of the bay. Rocks were uncovered in front of the bathing pavilion. An inspection of the beach next day, when an east wind was blowing, showed that a considerable part of the sand eroded 24 hours previously from near the jetty had been deposited in the north near the northern reef between the plunge line and the shore. The rocks in this area were covered by two to three feet of sand.

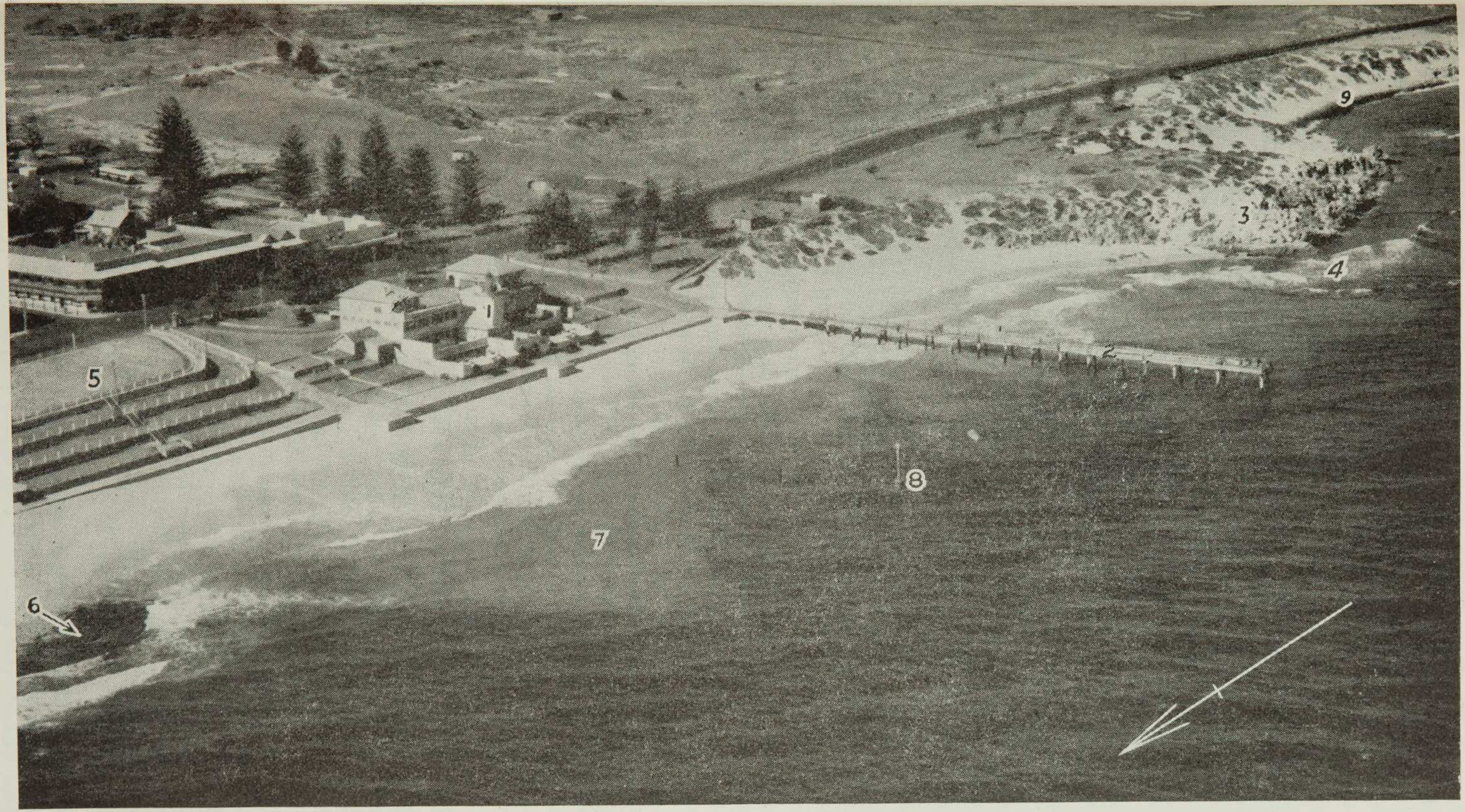
These events are interpreted as follows : it is apparent that the beach has been previously exposed to a sea that was nearly calm, due to an offshore or land breeze, and the beach had built up to such an extent that the slope of the swash zone was steep (in the vicinity of 1 in 6 or greater). The strong sea breeze blowing in from the S.W. drove the oblique waves onto a shore that was only stable for a land or offshore breeze. The altered condition produced a change in equilibrium so that the sand was moved back into the sea, tending to build up an offshore bar. However, the longshore drift set up by the oblique waves was so strong that it moved the sand in a northerly direction. Next day, with a return to land breeze conditions and the working of sand onto the shore by the action of the oscillatory waves, there was a building up of the beach some distance to the north of the point of erosion. The above sequence was eventually found to be most typical of events during the summer season.

Text fig. 8.

The beach immediately in front of the bathing pavilion on the 28th April, 1949. The photo was taken looking north from the wooden groyne at the base of the jetty. Note the rocks exposed at (1) and the foundations of the sea-wall exposed at (2).

Text fig. 9.

Looking north from Mudurup Rocks along the beach at Cottesloe as it was on April 28th, 1949. (1) Rock exposed by erosion. (2) Wooden groyne built in an attempt to stop erosion. (3) Rock exposed by erosion some 300 yards north of the jetty.



Text fig. 10.

An oblique aerial photograph of the beach at Cottesloe. (1) is the bathing pavilion, (2) the jetty, (3) Mudurup Rocks, (4) Contemporary wave-cut bench at the foot of Mudurup Rocks, (5) parking area, (6) North Reef, also a contemporary wave-cut bench, (7) is an area of freshly deposited sand covering the rocky floor of the bay, (8) a concrete pylon which, together with the other two piles visible, once supported the north side of a shark-proof swiming area, (9) the 5-ft. bench at the foot of Jarrad Street. The photo was taken in May, 1949.

At the beginning of the next summer season (November-December, 1949) the process described above was seen to be repeated many times, so that by the end of the year the beach was again retreating rapidly in the south (*i.e.*, between the jetty and Mudurup Rocks), and was being built up in the north in the vicinity of the north reef. Almost the entire beach was terminated by a steep cliff of sand on the sea side, so fast had the erosion been.

The sea breeze of 27th March was followed by a long period of rather calm conditions with light west, south-west and south-easterly winds. All the sand moved on the 27th March was worked back onto the beach, so that the rock bottom was again exposed.

On 27th April a north-west wind of gale force blew, which persisted for more than 24 hours. The resulting seas attacked the beach in the north spreading sand over the bottom of the bay, building an offshore bar, moving some sand into the southern end of the bay, and building up the beach just south of the jetty. After the gale had blown itself out, a light south-easterly wind blew for several days. This built up the beach along the length of the bay with the exception of the southern 150 feet or so, which remained a rocky beach for nearly all the year.

This type of cycle was repeated on numerous occasions during the winter. In the latter half of June it was noticed that strong rip currents were flowing from a constant point on the beach, just south of the jetty. Erosion of the sand was very active south of this point but not at all to the north. Moreover, seaweed and other drift material was accumulating to the north but not in the south. It was from this position that a strong rip was seen to be running during calm weather with a very light (Beaufort 0–1) offshore breeze blowing. This rip must have had a minimum velocity of two to three knots, persisting for 60 to 70 yards past the jetty in a north-westerly direction.

These rips prevented the beach from building up in the extreme south. It was only after the rips ceased that sand started to accumulate in the south, being assisted by the north-west winds working the sand down from the north and with the help of a southerly moving longshore current. The reef (Mudurup Rocks) then acted as a groyne, preventing the sand from leaving the bay. During the periods of quiescence the sand was built up on the beach as a swash bar. This beach in the southern part of the bay began building about 23rd August, and reached a maximum width about 8th November.

During the last few weeks of November, the summer season of strong sea breezes set in again and the beach began to be eroded to the south of the jetty. The initial erosion by the south-west wind at the close of the winter took place between a point about 50 to 60 feet south of the jetty to a point well north of the jetty. The first few strong south-west winds did not seriously attack the beach, and it was about 10 to 14 days before the beach began to be eroded under the influence of a south-west sea breeze. This lag in the initiation of erosion I believe was due to the presence of a south-moving longshore drift. It is only after this drift is stopped or reversed that erosion, due to the sea breeze, becomes effective. Another point is that up to a week before the erosion in the south became apparent, every north-west wind had been building the beach up to a considerable extent.

In conclusion, it may be said that the net effect of the north-west wind was to move the sand from the north to the south. Early in the year it appeared as though the beach was suffering destruction by the north-west wind, but this was due to the sand being spread out over rock bottom and being built into an offshore bar. As there was insufficient sand to build a bar to the maximum height of equilibrium for the particular set of waves, the beach was left bare of sand.

Text fig. 11.

The beach at Cottesloe looking north from Mudurup Rocks on 14th October, 1949. This photograph shows the beach as it was just prior to the commencement of erosion by the summer sea breezes.

From the presence of rips in the southern part of the bay it appeared to take up to two months after the end of summer sea breezes to reverse the strong south to north longshore drift. Once this reversal had taken place, then rapid accumulation of sand resulted along the whole of the beach, particularly in the extreme south of the bay.

(2) *Progressive Changes.*

Little evidence can be found in the way of photographs, paintings, etc., on the state of the beach at Cottesloe prior to the building of the bathing pavilion. Undoubtedly a good beach existed, according to all verbal reports, the present beach being a mere shadow of its former self. Both from the verbal reports of many people and from the observations during 1949, it would appear that the disappearance of the beach has been gradual, only becoming very apparent over the last 10 to 12 years.

From the general discussion of sand movements in the Fremantle area, it was apparent that the building of the harbour moles formed an effective blockage to the northward movement of sand. As the sand supply from the beaches between Cottesloe and Leighton was diminished, due to erosion without seasonal replacement, the rate of erosion of the beach at Cottesloe was accelerated until the present state of affairs was reached.

The year of observation (1949) was to some extent unusual in that almost no winds south of west were recorded for two or three months during the winter season, thus giving the north-west winds an opportunity to rebuild the area, so that an excellent beach was re-established by the middle of November. Nevertheless it required only a few weeks of sea breezes then to carry it away once more.

Text fig. 12.

Looking north from Mudurup Rocks. This photograph was taken in 1906 and shows the beach as it was before the improvements, such as bathing pavilion and promenade, were erected. Note the good beach and the presence of high sand hills behind the beach.

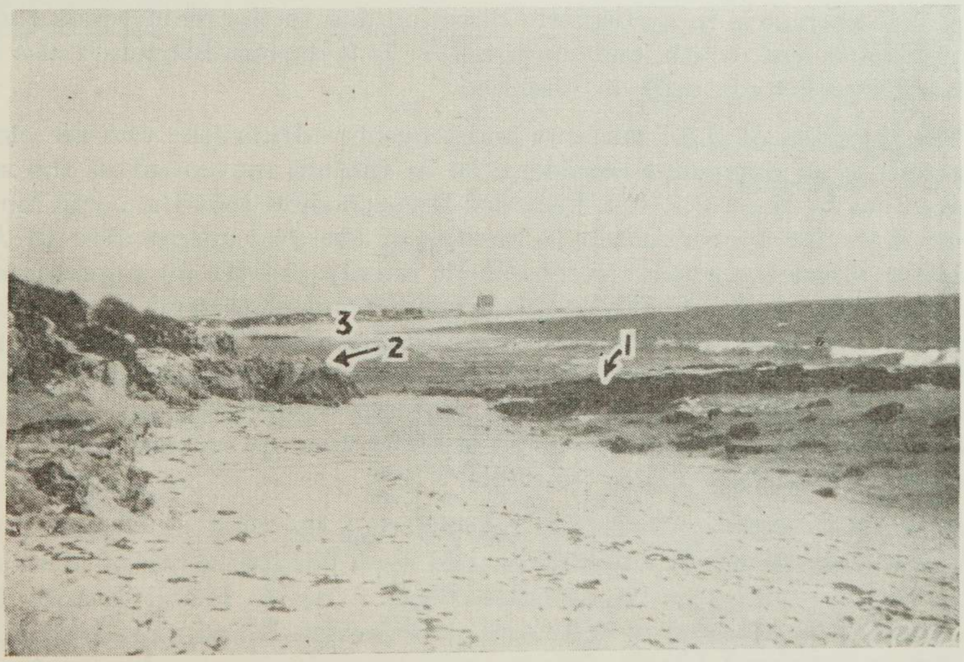
(3) *Causes of the Changes.*

The overall conditions existing in the area both before and after the Fremantle moles were built has been discussed. It is now proposed to deal in particular with the section of the coast from North Mole to Swanbourne. Within this area there is a considerable sector that shows marked accumulation of sand. Another equally long stretch of beach has suffered scouring. These two sections are from North Mole to Leighton (accumulation) and Leighton to Mudurup Rocks (scouring) respectively. North of Mudurup Rocks the beach suffers seasonal variation in the amount of sand being scoured and deposited but no apparent net change.

It was suggested by the writer (Kempin, 1949) that the sand immediately to the north of the North Mole was derived predominantly from dredgings that had been and are still being dumped in the sea west of that area. This view is still held. Somerville (1945) suggested that the accumulation of sand north of the mole was due primarily to the erosion of the beaches around Cottesloe and secondarily to the dredgings from Fremantle Harbour. Hall and Herron (1950) tested the idea that a beach could be built up by dumping dredgings out to sea near Long Beach, New York, but their results were inconclusive. Over the period of their observations (12 months) there was no evidence to prove whether the sand was moving or whether it was settling. The sand dumped off North Fremantle, however, has had some 50 to 60 years to work in to the shore as against only one year at Long Beach.

Certainly much sand from Cottesloe is now on the beaches in the North Mole area, but the volume of sand accumulated here is far greater than the volume of sand eroded farther north. Nevertheless, the observations still indicate that the main movement of sand is northwards. Thus, it is only the sand that moves south in the winter time into the prograding " shadow " area of the mole that is retained. At first, it was thought from the nature and extent of the accumulated sand here, that any drift from the north could be discounted on the grounds that the sand accumulation did not encroach along the groyne. But the groyne was specifically designed by C. Y. O'Connor in such a manner as to defeat such a movement or encroachment of sand ; it is not built at right angles to the coast, but is directed W.S.W., and it is carried out into six fathoms of water.

Regarding the eroded beaches north of Leighton, from a comparison of their present state and a description of Cottesloe as it was about the turn of the century by Somerville (1945), it is apparent that erosion has been very active. Further, it is clear that it is only the old beach that has been eroded and very little erosion of the sand hills at the back of the beach has taken place. An examination of the coast between Swanbourne and Leighton shows that almost the entire beach over this distance is underlain by a rock bench. In places this bench forms a contemporary wave-cut platform which is horizontal at about low water mark, in others it forms a bench three or five feet above datum. At Mudurup Rocks is a contemporary wave-cut platform or bench, but the rocks at the foot of Jarrad Street are part of a 5 ft. bench. From Pearse Street to Leighton a 3 ft. bench is almost continuous.



Text fig. 13.

Looking south from approximately the foot of Pearse St., Cottesloe. This photograph shows a typical beach for that part of the coast from Mudurup Rocks to Leighton. (1) 3-ft. bench exposed by erosion of the beach. (2) Coastal Limestone outcrop on the beach. (3) Good "built-up" beach just south of Leighton. In the background can be seen the wheat silo and some of the harbour installations of Fremantle

Since these are platforms of hard rock, then the sandcover over them could never have been extensive. For this reason it is held that only a small amount of the sand north of the Fremantle mole has come from the Cottesloe area. Mudurup Rocks and the various rock benches have also saved the sand hills behind the beach from erosion because they break the force of the waves and reduce their destructive power.

With the stripping of the beach between Mudurup Rocks and Leighton, the northerly longshore drift moving around Mudurup Rocks into the bay of Cottesloe is " barren " of sand. Thus, it is not surprising that, with a longshore drift from the south, the beach at Cottesloe disappears rapidly as no sand is being brought in to replace that eroded.

Towards the end of summer, when Cottesloe beach has been nearly eroded away, the effect of this " barren " littoral drift begins to be felt farther north at Eric Street Pool and along the coast almost to Swanbourne.

During the winter the Mudurup Rocks act as a groyne to the southerly drift, so that the sand builds up in the bay. However, because the summer conditions are so effective in removing the sand from the bay, winter conditions never build up sand against the " groyne " to its maximum capacity. If the bay were filled up to its maximum, then sand would travel around Mudurup Rocks and tend to replenish the beaches farther south. As one proceeds north the effect of the North Mole on the movements of beach sands becomes progressively less until, in the vicinity of City Beach, it is negligible.

V. CONCLUSIONS.

From a broad study of the unit area from Cockburn Sound and Fremantle to Scarborough, the general seasonal movements of sand have been ascertained. These movements are closely linked with the directions of the surface drifts associated with the prevailing weather cycles. During the summer months the surface current is in a northerly direction due to the main winds coming from the south-east, south, and south-west. It is during this period also that the northerly littoral drift is observed.

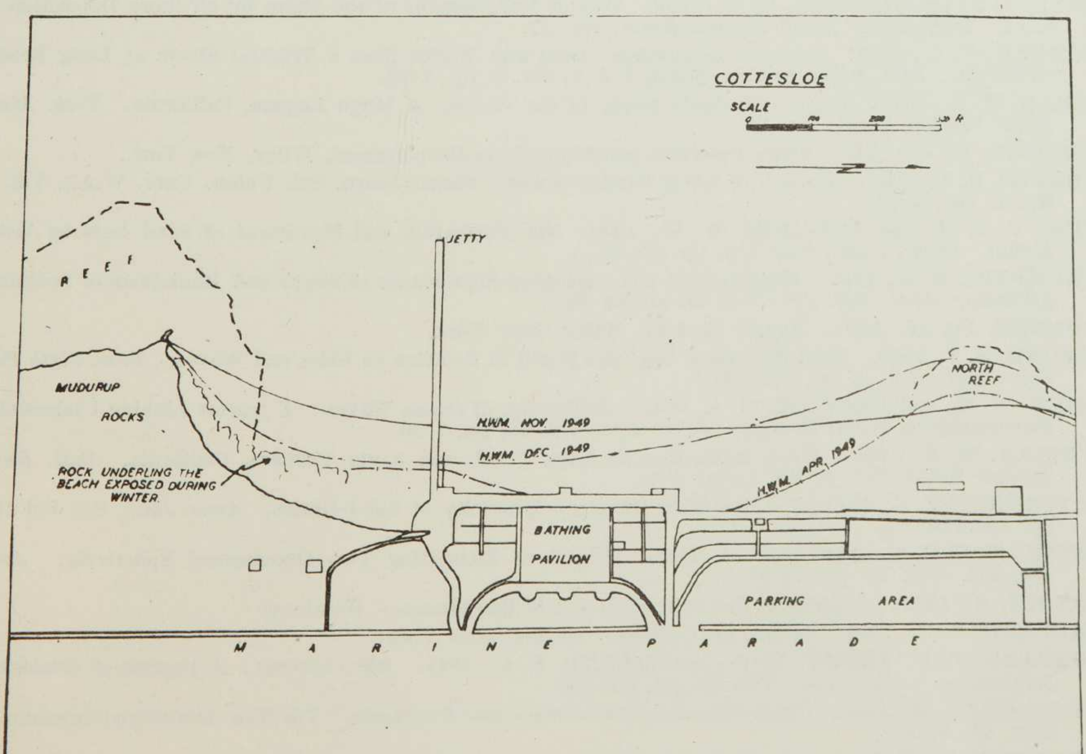
The duration of these currents and longshore drifts (the two are closely connected) is an important consideration in the net movement of the sand. Observations by the C.S.I.R.O. Fisheries Division show that the north-moving current flows for approximately 8 months of the year (September to April inclusive), whilst the southerly movement is only present for approximately 2 months (June to July). From this a net movement of sand in a northerly direction would be expected, and the form of the coastal features, such as river mouths, headlands, islands, tombolos, etc., certainly does indicate an overall movement of sand from south to north, although observations on actual movement in various localities along the coast show that the amount and speed of movement of sand is highly variable.

Thus, the conclusion has been reached that the sand movement (in the whole area from south of Point Peron and even possibly south of Mandurah) is in a northerly direction up the west coast of Garden Island towards Rottnest Island. As the sand moves north past Garden Island, part is carried to the east past Carnac Island, forming two large east-west submerged ridges of sand known as Parmelia and Success Banks. This east-west orientation of these sandbanks appears to be due to the action of deep sea swell coming in through openings in the north-south chain of reefs between Garden Island and Rottnest. As stated previously, this explanation is only tentative, but it is certain that the source of the sand is from the south. The constitution of the sand, being very fine and over 90 per cent. carbonate, suggests that it is the fine fraction from beaches. The general type of sand agrees closely with the average sand from Garden Island.

The inner part of the Parmelia and Success Banks merge with the coastline and have clearly caused large quantities of sand to be deposited in the immediate vicinity of South Fremantle and Fremantle itself. Old drawings of Fremantle show the site of the town as a low-lying tombolo that had built up from the south. South Beach itself is a " reclaimed " or " built up " offshore bar. It seems quite likely that the mouth of the Swan was displaced northward until it took up its present position, and, before the harbour works there, it flowed over a rock bar.

North of Point Rous the northward movement of sand before the groynes were built was probably not very noticeable. Here, in fact, the movement may have been rather well-balanced (to the north in the summer and to the south in the winter). However, after the building of the North Mole had interrupted the normal longshore drift, both the dumping of dredgings and the southerly drift of sand along the shore caused sand to be trapped and a large deposit was formed between here and Leighton. The dredgings no doubt account for the large quantities of rock debris that is found along the beach here. The mole thus formed has a " shadow effect " on the northward-moving drift and causes strong wave refraction in towards the shore.

At Leighton Beach the " shadow effect " and refraction of the mole ceases, and from here northwards the northerly longshore drift sweeps the coast all through the summer season. As it comes into the coast devoid of sand, scouring begins once more until a full load is being carried. Over the years the combined effort of the southerly drift moving sand into the " shadow area " behind the mole, and the scouring of the beach by the northerly current, has stripped the beaches between Leighton and Mudurup Rocks of all available sand.



Text fig. 14.

Shows the position of high water marks (H.W.M.) at various times of the year. (Note: The change in position of H.W.M. from November, 1949 to December, 1949. This clearly shows the effect of the sea breezses in moving sand northward.

At Cottesloe it is found that the reef out from Mudurup Rocks is acting as a low groyne, preventing the sand moving south past this point under the influence of the south-moving winter drift. In summer the northerly drift, which is running from an area where sand is not available (*i.e.*, Leighton-Mudurup), enters the bay at Cottesloe and erodes the beach here. The winter-accumulated sand is thus the first beach which is capable of supplying material, and in early summer yields large quantities of sand which is moved northward. When Cottesloe has been stripped, the scouring action moves northward.

Farther north the supply is sufficient to meet the demand, so that erosion is not very apparent, although at City Beach some erosion was taking place until a groyne was built which stabilised the coast to a very large extent.

The recommendations made at the conclusion of the survey were that as the sand is brought into the beach at Cottesloe during the winter months, the problem is to keep it there during the summer, and to this end the construction of a groyne was suggested. The site of this groyne would be Mudurup Rocks in such a direction as to cause the " barren " summer northerly drift to be deflected from the bay and to stimulate wave refraction to maintain the beach in a manner analogous to that observed at Leighton.

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